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Modeling Signal-to-Noise Ratio of Otoacoustic Emissions in Workers Exposed to Different Industrial Noise Levels

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Abstract

Introduction: Noise is considered as the most common cause of harmful physical effects in the workplace. A sound that is generated from within the inner ear is known as an otoacoustic emission (OAE). Distortion-product otoacoustic emissions (DPOAEs) assess evoked emission and hearing capacity. The aim of this study was to assess the signal-to-noise ratio in different frequencies and at different times of the shift work in workers exposed to various levels of noise. It was also aimed to provide a statistical model for signal-to-noise ratio (SNR) of OAEs in different frequencies based on the two variables of sound pressure level (SPL) and exposure time. **Materials and Methods:** This case–control study was conducted on 45 workers during autumn 2014. The workers were divided into three groups based on the level of noise exposure. The SNR was measured in frequencies of 1000, 2000, 3000, 4000, and 6000 Hz in both ears, and in three different time intervals during the shift work. According to the inclusion criterion, SNR of 6 dB or greater was included in the study. The analysis was performed using repeated measurements of analysis of variance, spearman correlation coefficient, and paired samples *t*-test. **Results:** The results showed that there was no statistically significant difference between the three exposed groups in terms of the mean values of SNR ($P > 0.05$). Only in signal pressure levels of 88 dBA with an interval time of 10:30–11:00 AM, there was a statistically significant difference between the right and left ears with the mean SNR values of 3000 frequency ($P = 0.038$). The SPL had a significant effect on the SNR in both the right and left ears ($P = 0.023$, $P = 0.041$). The effect of the duration of measurement on the SNR was statistically significant in both the right and left ears ($P = 0.027$, $P < 0.001$). **Conclusion:** The findings of this study demonstrated that after noise exposure during the shift, SNR of OAEs reduced from the beginning to the end of the shift.

Keywords: Cochlea, noise, occupational, otoacoustic emissions, signal-to-noise ratio

Introduction

Environmental noise has been identified as one of the harmful factors affecting the health of workers, and it is one of the major occupational risks.[1] Noise is known as the most common occupational risk factor in the world and is considered as the most common cause of physical work related injuries.[2]

The performance of various parts of the body like hearing, blood circulation, mental activities, and working performance may be negatively affected by noise levels beyond the threshold level.[3] When a person is exposed to noise, he/she may suffer from anatomical, nonauditory, and auditory effects.[4] Hearing loss is the most important and most common effect of occupational noise exposure.[5]

The auditory effects of noise exposure are noise-induced hearing loss (NIHL). In particular, the auditory effects can include the shift of hearing threshold and deterioration of speech perception.[4] Temporary changes in hearing because of overexposure are not only observed in the temporary threshold shift (TTS), but have also been shown to alter otoacoustic emissions (OAEs). In OAE or OAE testing, the sounds that the ear produces itself are recorded. For the first time, Kemp in 1978 reported OAEs.[6]

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Several studies have used industrial methods and pure-tone testing to determine the effects of noise on hearing loss and probable mechanisms that may lead to its incidence. However, such tests have some limitations; for example, they are not objective, have low sensitivity in diagnosis of defect, and do not provide detailed information about the changes caused by exposing to noise. Thus, there is a need for more accurate tests. Pure-tone audiometry is not able to detect early damages to hearing system at early stages and this test is only able to measure damages after the onset of irretrievable effects to hearing system.[7] Distortion-product otoacoustic emission (DPOAE) is a type of emission that can be used to investigate the features of the cochlea in a frequency-specific manner.[8,9]

In the past several years, DPOAEs have been used as a clinical test to measure the status of cochlear, diagnose hearing disorders, monitor potential progressive hearing disorders, and determine newborn hearing.[10] DPOAE is the reaction of the inner ear to two pure-tone stimuli (the primaries f_1 and f_2), which cause a series of distortion products that are common at the frequency $2f_1–f_2$. Overall, according to the two-source model, it is believed that DPOAE is produced by at least two sources.[11,12] The two components of DPOAE are (1) the distortion component generated at the f_2 place and (2) the reflection component generated at the $2f_1–f_2$ place.[13] In this study, we used DPOAE test to evaluate the performance of cochlea. DPOAE is one of the features of different types of OAEs. In DPOAE measuring, the emissions made and reinforced in cochlea by certain frequencies of f_1 and f_2 are recorded.[14]

DPOAE, which is an objective and nonaggressive test, uses the features of frequency sensitivity to evaluate the cochlear stress.[15] As a valid test, DPOAE is used to identify cochlear stress. It does not need listener's cooperation and is used for studies on animals, infants, and old people. Signal-to-noise ratio (SNR) is an index that compares the level of a desired signal to the level of background noise and is defined as the ratio of signal power to the noise power, often expressed in decibel. The SNR can be used to demonstrate the difference between the measured OAE emission and the background noise level. Accordingly, the positive values can specify a measurable response over the background noise.[4,16,17]

However, far too little attention has been paid to evaluate the relationship between the SNR of OAEs with different levels of noise exposure at different signal pressure levels. This study therefore is aimed at addressing this lacuna in the literature.

More specifically, this study was designed to:

(1) Provide a statistical model of the SNR for different frequencies in the right and left ears at different times based on various levels of exposure to different noise exposure levels.
(2) Determine SNRs in different frequencies in the right and left ears of the workers exposed to various levels of noise at three time intervals.

Materials and Methods

Study population and industry selection

The study population included male workers of Gol Gohar Mining and Industrial Company, in Sirjan, which is located in southeast Iran. The study was conducted during autumn 2014. Right before conducting the study, the subjects' health status with regard to the hearing status, as well as heart and vascular and mental condition, was monitored by reviewing their medical records; accordingly, the healthy individuals were enrolled in the study. We selected Gol Gohar Mining and Industrial Company as the place of study as it had the appropriate conditions for the study. Workers were not exposed to thermal stress. There were also no main vibration sources. Because of sound pressure level (SPL) variability in the measurement domains, ±5 dBA was thought to be a suitable standard deviation for this variable.

Sampling method

This case–control study had a control group and two case groups. The samples were divided in a way that a fixed number of subjects would be placed in each of the three groups. On the basis of the previous studies, the researchers decided to include 45 participants in general.[1,18-20] As a result, the sample size in each group was 15 people.

Study design

In this study, the participants filled out a form on demographic data. Further, their body mass index (BMI) was measured and recorded. The workers were divided into the following three groups on the basis of noise exposure: (1) 15 office workers as the control group with exposure to low level of noise, (2) 15 workers from the manufacturing departments as the case group exposed to medium level of noise, and (3) 15 workers from the manufacturing departments as the other case group exposed to high level of noise. The selected workers in the exposed groups (cases) did not use any hearing protection devices and performed routine light work (based on ISO 8996).[21] The SPLs intensities, which were determined as the environmental variables, were measured at different places of the company. An experienced audiologist conducted DPOAE test for all the subjects in the control and both case groups at the following three different time intervals: at the beginning of the shift and before exposure to noise (7:30–8:00 AM), during exposure to noise (10:30–11:00 AM), and (13:30–14:00 PM) at frequencies of 1000, 2000, 3000, 4000, 6000 Hz. Before conducting DPOAEs, the following issues were checked for each subject: (1) the external ear should not be blocked; (2) the probe should be positioned properly inside the ear canal; (3) the probe should completely cover the ear canal; (4) there should be no middle ear pathology; and (5) the subject should be calm and silent during the test.

Measurement tools

Noise

A sound level meter (CEL-440, CASELLA, USA) was used to measure the noise at each workstation based on ISO 9612.[22] To calibrate the sound level meter exactly before the measurements, CEL-282 calibrator (CASELLA, USA) was used.

Signal-to-noise ratio

To measure SNRs at frequencies 1000, 2000, 3000, 4000, and 6000 Hz, the DPOAE test device (Vivosonic 2.5.2; Vivosonic, Toronto, Canada) was used. The DPOAE test was selected as the desired test because it has a frequency selective nature. All the participants were placed in sedentary positions during the test. The f_2/f_1 was set as 1.22 and the levels of the signals were $L_1 = 65$ dB and $L_2 = 55$ dB SPL, respectively. Small probes were used to send the outer ear canal audio frequencies to the tympanic membrane; the probes received the reflected sounds that were a little delayed by a microphone which was installed in the probe. A silent room was used to carry out the test procedures and recordings. In this study, the SNR in $2f_1–f_2$ was considered and evaluated as a response to DPOAEs at 1000, 2000, 3000, 4000, and 6000 Hz in the subjects' right and left ears, separately. The researchers selected this range of frequencies because within this range ears are prone to hearing loss. Distortion-product otoacoustic emission–noise floor (DP-NF) was also used to calculate SNRs for the three groups. The SNR of 6 dB or greater was considered as the inclusion criterion.[23,24]

Data analysis

Descriptive methods such as mean, standard deviation, and frequency were used to summarize the data. Shapiro–Wilk test was used to examine normality of the data. Given that the data were measured repeatedly over time, the method of repeated measurements analysis of variance was used to analyze the data and provide the model. All the assumptions of this method were evaluated before the study. To check the difference between means, paired samples *t*-test was used.

Statistical Package for the Social Sciences (SPSS) version 18 (SPSS, Inc., Chicago, Illinois, USA) was used to analyze the collected data. The *P*-value of less than 0.05 was determined as the significance level.

Ethical consideration

This study was done based on the ethical principles of Ethics Committee of Tehran University of Medical Sciences (ID: 1394.51). A written informed consent form was obtained indicating workers' willingness to participate in the study. The subjects were ensured that the data would remain confidential and used for the research purposes only. The participants had also an unconditional and absolute right to withdraw at any time.

Results

Results of analyzing demographic characteristics

Table 1 presents the mean age and BMI of the three studied groups.

Statistical model of signal-to-noise ratio

To provide a model for SNR, repeated measurements analysis of variance was used. The statistical model of SNR for the right and left ears at different frequencies using the two variables of SPL and time (dummy variable) is shown in Tables 2 and 3.

The mixed model of signal-to-noise ratio based on sound pressure level, exposure time, and frequency

Table 4 illustrates the results of using the mixed model (mixed effects model) for calculating the interactive effect of SPL, exposure time, and frequency on SNR.

Estimation of covariance parameters is presented in Table 5.

As illustrated in Table 4, the final model of SNR is presented in the following form.

$$\text{Signal} - \text{to} - \text{noise ratio(dB)} = 28.64 - 0.081\text{SPL} - 0.34\text{Time} - 0.002F$$

where SPL is sound pressure level (dB), time is exposure time (h), and F is frequency (Hz). In the statistical model above, the exposure time was considered to be from 7:30 AM to 14:00 PM (i.e., the exposure time ranges from 0 to 6.5 h).

Result of the alterations in the SNRs

In this study, SNR ≥ 6 was considered as inclusion criterion. The evaluation of SNRs showed that all SNR values were acceptable because SNR values were more than 6 at all studied frequencies. The mean of the SNRs at 1000, 2000, 3000, 4000, and 6000 Hz frequencies in the right ear, at different SPLs and time intervals, are shown in Figures 1–3. It is clear that with the passage of time toward the end of the shift work, there was a decline in SNR values from the right ear. Such a decline occurred at all frequencies and all SPLs.

Discussion

This study was conducted among 45 workers in Gol Gohar Mining and Industrial Company. In this study, DPOAE test was used to evaluate changes in the SNR of OAEs in 1000, 2000, 3000, 4000, and 6000 Hz frequencies after each assessment. The results showed that age, BMI, and work experience had no significant impact on SNR ($P > 0.05$). Studies have shown that with increasing age, amplitudes of DPOAE reduces.[25] In this study, age had no effect on the SNR. Hence, after adjusting the impact of age, BMI, and work experience, the effects of signal pressure level and the time of exposure on the SNR were analyzed.

Table 1: Demographic features of the subjects

Variables	Control group exposed to noise level 72 dBA Mean ± SD	Case group exposed to noise level 88 dBA (n = 15) Mean ± SD	Case group exposed to noise level 103 dBA (n = 15) Mean ± SD
Age (years)	28.8 ± 2.05	30.1 ± 2.37	–
BMI (kg/m^2)	25.11 ± 2.28	25.50 ± 3.25	29.4 ± 2.63
Work experience (months)	26 ± 7	31 ± 9	25.52 ± 2.97

Table 2: Statistical model of signal-to-noise ratio of otoacoustic emissions at different frequencies in the right ear

Frequency (Hz)	SNR (dB) model
1000	$\mathrm{SNR} = 10.065 + 0.088\mathrm{SPL} + 3.357\mathrm{Time}_{7:30\text{–}8:00} + 1.486\mathrm{Time}_{10:30\text{–}11:00}$
2000	$\mathrm{SNR} = 19.89 - 0.01\mathrm{SPL} + 2.55\mathrm{Time}_{7:30\text{–}8:00} + 1.29\mathrm{Time}_{10:30\text{–}11:00}$
3000	$\mathrm{SNR} = 11.79 + 0.07\mathrm{SPL} + 3.62\mathrm{Time}_{7:30\text{–}8:00} + 1.91\mathrm{Time}_{10:30\text{–}11:00}$
4000	$\mathrm{SNR} = 13.24 + 0.05\mathrm{SPL} + 2.44\mathrm{Time}_{7:30\text{–}8:00} + 1.31\mathrm{Time}_{10:30\text{–}11:00}$
6000	$\mathrm{SNR} = -0.63 + 0.2\mathrm{SPL} + 2.22\mathrm{Time}_{7:30\text{–}8:00} + 0.63\mathrm{Time}_{10:30\text{–}11:00}$

Table 3: Statistical model of signal-to-noise ratio of otoacoustic emissions at different frequencies in the left ear

Frequency (Hz)	SNR (dB) model
1000	$\mathrm{SNR} = 3.92 + 0.16\mathrm{SPL} + 3.82\mathrm{Time}_{7:30\text{–}8:00} + 1.54\mathrm{Time}_{10:30\text{–}11:00}$
2000	$\mathrm{SNR} = 21.76 - 0.3\mathrm{SPL} + 2.34\mathrm{Time}_{7:30\text{–}8:00} + 0.48\mathrm{Time}_{10:30\text{–}11:00}$
3000	$\mathrm{SNR} = 18.85 - 0.005\mathrm{SPL} + 2.82\mathrm{Time}_{7:30\text{–}8:00} + 1.38\mathrm{Time}_{10:30\text{–}11:00}$
4000	$\mathrm{SNR} = 15.96 + 0.04\mathrm{SPL} + 3.17\mathrm{Time}_{7:30\text{–}8:00} + 1.02\mathrm{Time}_{10:30\text{–}11:00}$
6000	$\mathrm{SNR} = 9.3 + 0.06\mathrm{SPL} + 5.58\mathrm{Time}_{7:30\text{–}8:00} + 3.65\mathrm{Time}_{10:30\text{–}11:00}$

Table 4: The parameters of the final model of signal-to-noise ratio obtained by calculating the mixed effects of sound pressure level, exposure time, and frequency

Model parameter	Estimate	Standard deviation	Degrees of freedom	t-Coefficient	P-value	95% confidence interval	
						Lower bound	Upper bound
Intercept	28.64	2.95	19	9.70	0.001	22.47	34.82
SPL	−0.081	0.032	18	−2.51	0.022	−0.15	−0.013
Time	−0.34	0.11	18	−2.99	0.008	−0.58	−0.10
Frequency	−0.0002	0.0001	83	−1.36	0.175	−0.00052	9.69

Table 5: Estimation of covariance parameters

Parameter		Estimate	Standard deviation	Z-score	P-value	95% confidence interval	
						Lower Bound	Upper Bound
Repeated measures	CS diagonal offset	7.53	1.17	6.4	0.001	5.56	10.21
	CS covariance	1.54	1.04	1.4	0.13	−0.50	3.59

The results showed that the SPL also had a significant effect on the SNR in both right and left ears ($P = 0.023$, $P = 0.041$). The effects of time on SNR in the right and left ears were significant ($P = 0.027$, $P < 0.001$); the ratio decreased in the left and right ears in a working shift, gradually from the beginning to the end of the shift. There was a statistically significant relationship between SNR values in the right and left ears at the two specific time intervals of (7:30–8:00 AM) and (13:30–14:00 PM), and with an increase in the duration of exposure, the SNR reduced.

In this study, the SNR ≥ 6 was considered as a measure of acceptable response of the SNR. In most studies, the effect of SNR on DPOAE is evaluated in 2000, 3000, and 4000 Hz frequencies, and SNR ≥ 6 is considered as the acceptable response.[8,20] After the evaluation of SNR values, it was found that the SNR values at all frequencies were more than 6 in the right and left ears; therefore, all (100%) SNR values were considered as acceptable responses.

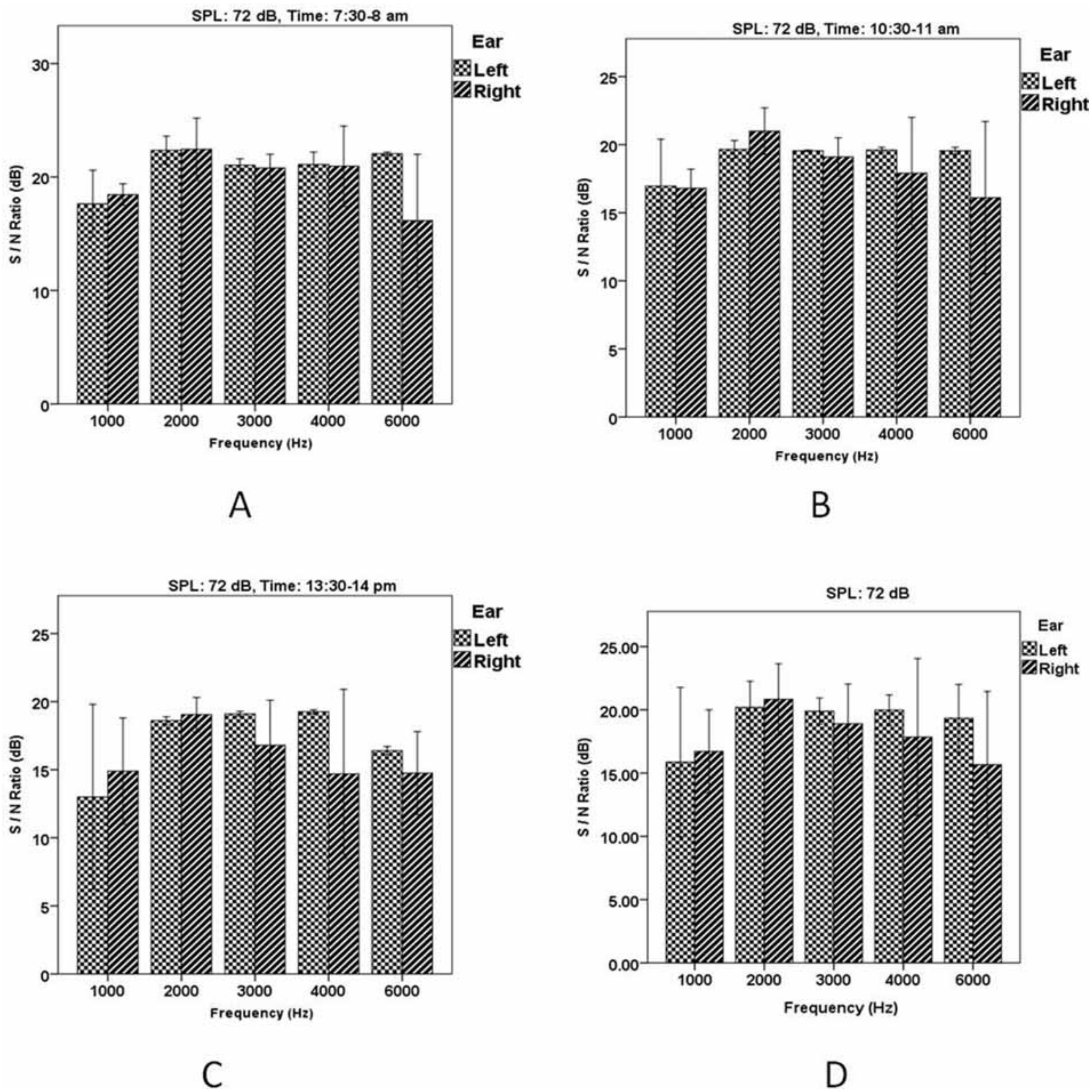

Figure 1: Result of the alterations in the SNRs at studied frequencies in the right and left ears in the control group exposed to noise level (72 dBA). (A–D) The mean values of SNR in the right and left ears at similar frequencies. (A) The mean SNR values in the time interval of 7:30–8:00 AM. (B) The mean SNR values in the time interval of 10:30–11:00 AM. (C) The mean SNR values in the time interval of 13:30–14:00 PM. (D) The total of mean SNR values in the three time intervals

Attias *et al.*[26] concluded that DPOAE test clearly indicates changes among individuals who are exposed to noise compared to the participants in the control group. Thus, it is a suitable test for evaluating the performance of cochlea.

As indicated in Table 3, SPL has a significant effect on the SNR ($P = 0.022$). The effect of exposure time on the SNR was also significant ($P = 0.008$). Frequency, however, had no statistically measurable influence on the SNR ($P = 0.175$).

The results of paired samples *t*-test demonstrated that there was no significant difference in the mean values of SNR of similar frequencies and the SPL of 72 dBA in three different times and the total time period ($P > 0.05$).

Moreover, the results of paired sample *t*-test showed that there was no significant difference in the mean values of similar frequencies in the right and left ears of the 88 dBA group in time periods of 7:30–8:00 AM and 13:30–14:00 PM. There was also no significant difference in the total time period ($P > 0.05$). In contrast, there was a significant difference in the mean values of SNR in the frequency of 3000 in the 88 dBA group in the time period of 10:30–11:00 AM in the right and left ears ($P = 0.038$).

Other results showed that there was no significant difference in the mean values of SNR of similar frequencies in SPL of 103 dBA in the three different time periods and the total time period ($P > 0.05$).

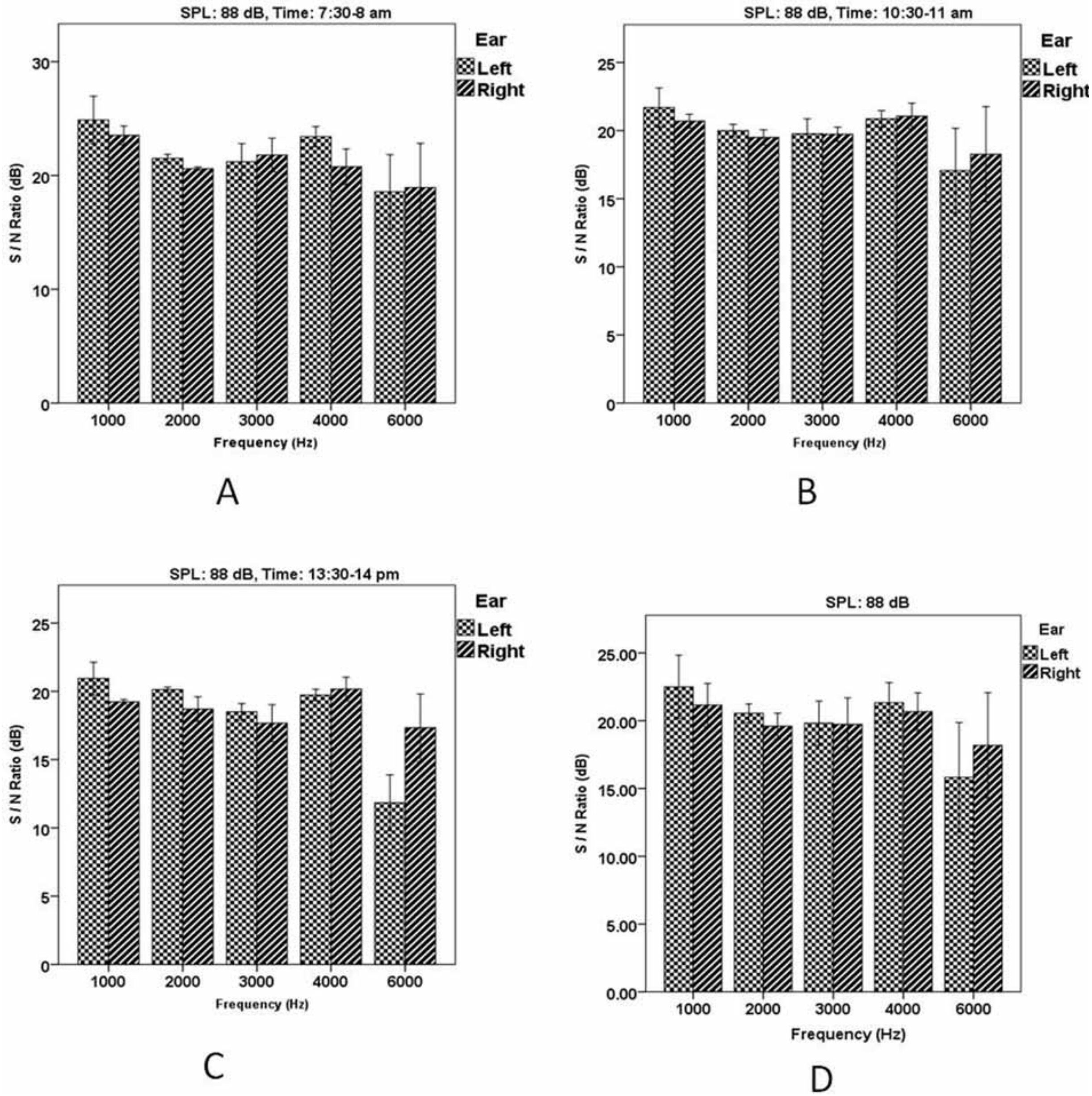

Figure 2: Result of the alterations in the SNRs at studied frequencies in the right and left ears in case group exposed to noise level (88 dBA). (A–D) The mean values of SNR in the right and left ears at similar frequencies. (A) The mean SNR values in the time interval of 7:30–8:00 AM. (B) The mean SNR values in the time interval of 10:30–11:00 AM. (C) The mean SNR values in the time interval of 13:30–14:00 PM. (D) The total of mean SNR values in the three time intervals

In this study, to record DPOAE ($2f_1–f_2$), two signals of f_1 and f_2 ($f_2 > f_1$) were used. The f_2/f_1 ratio was kept at 1.22 and the levels of the signals were $L_1 = 65$ dB and $L_2 = 55$ dB. The test was performed at 1000, 2000, 3000, 4000, and 6000 Hz frequencies with an SNR ≥ 6.

Using a protocol f_2/f_1 1.22, $L_1 = 65$ and $L_2 = 55$ dB SPL, and three points per octave, Poole *et al.* performed the DPOAE test for 33 subjects. They included the SNRs above zero in their analysis. Their proportion measurable tests ranged between 99 and 82%, and the lowest proportion was identified at 4 kHz.[27]

Marques and da Costa[28] indicated that there is a correlation between the lack of response to DPOAE among workers who are exposed to noise in the work environment and the frequency range that leads to hearing loss. They concluded the following: (1) there is a correlation between the exposure time to work noise and lack or reduction of DPOAE; (2) there is a correlation between high SPLs and the findings that are based on changes in the OAEs; (3) with respect to noise exposure, the frequencies of 3000, 4000, and 6000 are more sensitive; and (4) DPOAE is a suitable way for early detection of physiopathologic changes, which are the result of exposure to noise in the working environment.[28] The results of this study are completely in line with those of Marques and da Costa. This study indicated that SPL and exposure time significantly affect the SNR, in the sense that, as the SPL and exposure time go up, the SNR reduces.Janssen and Müller[29] found that, as SNR increases,

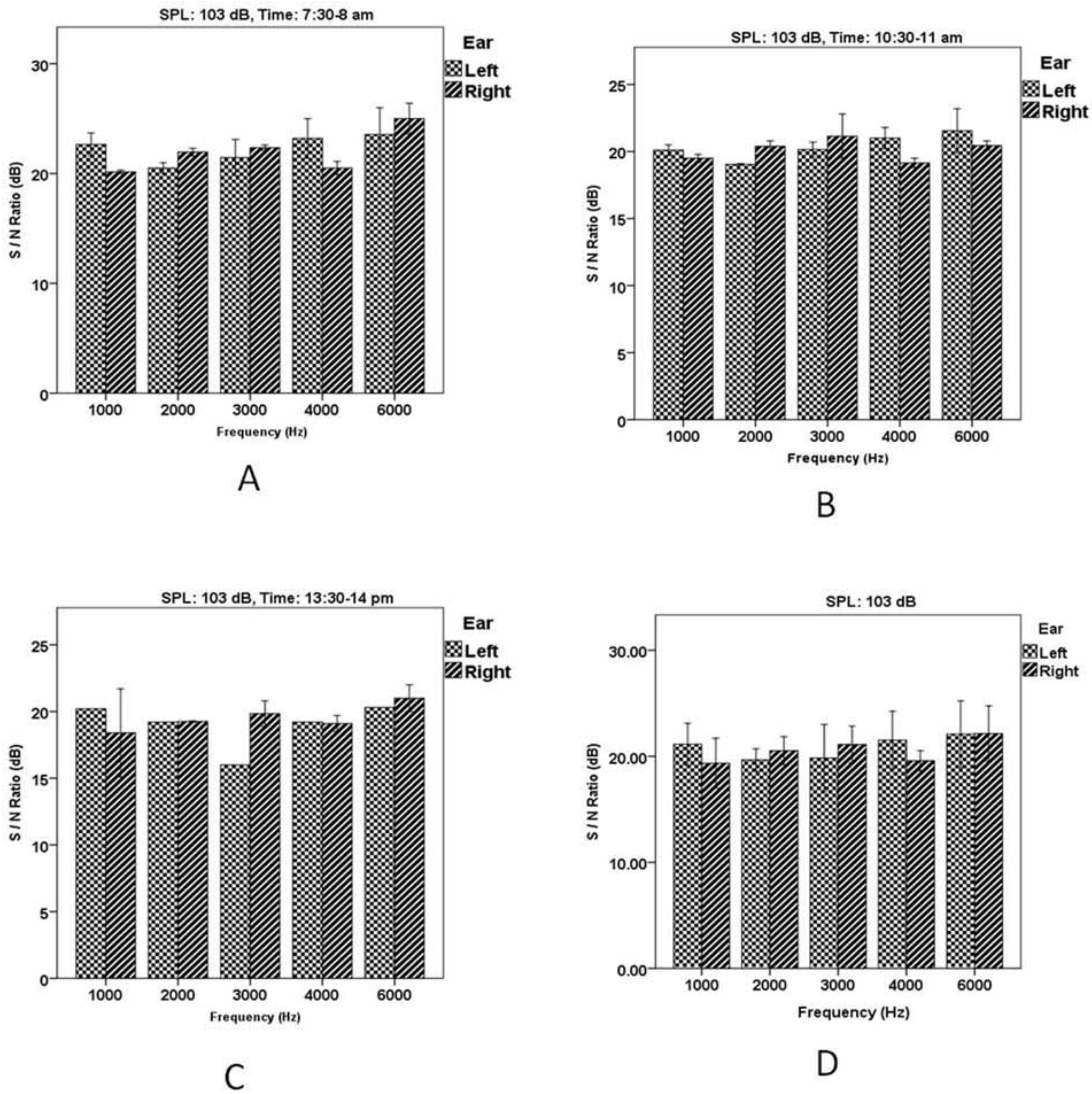

Figure 3: Result of the alterations in the SNRs at studied frequencies in the right and left ears in case group exposed to noise level (103 dBA). (A–D) The mean values of SNR in the right and left ears at each frequency. (A) The mean SNR values in the time interval of 7:30–8:00 AM. (B) The mean SNR values in the time interval of 10:30–11:00 AM. (C) The mean SNR values in the time interval of 13:30–14:00 PM. (D) The total of mean SNR values in the three time intervals

standard deviation goes up exponentially, that is, the higher the SNR, the lower the standard deviation. They claimed that standard deviation is not a good indicator of the repeatability of the DPOAE test.[29] Similarly, in this study, the increase of SNR resulted in the decline of standard deviation. Thus, in frequencies with lower SNR, standard deviation is higher and vice versa. Overall, in most of the responses, the standard deviation was within the acceptable range. In fact, in many cases, it was lower than one.

Sutton *et al.*[30] studied DPOAE among a group of industrial workers who were exposed to noise. They discovered that the time period for retrieving the domains of DPOAE was very similar to the measured behavior for TTS. They, therefore, stated that exposure to noise reduces the levels of DPOAE.[30] This study also indicated that, as the exposure time goes up, the SNR mean decreases.

In this study, a statistical model was presented for the SNR in different frequencies. The model was in very close agreement with the measured values. As a result, it can be concluded that SNR decreases over time during a shift work; moreover, SPL and the duration of noise exposure have a statistically significant impact on the SNR.

Strong Points and Limitations

This study has the following two novelties: (1) to the best of our knowledge, no study has evaluated the relationship between the increase in the SPL and the responses of OAEs. In this study, SNR of OAEs was measured in the control group and the group exposed to industrial noise, at the beginning of the shift and after 3 and 8 h of work. The results of this study showed the significant relationship between the increase in SPL and OAEs in the ears of human samples; (2) as far as we know, no study has presented a statistical model for SNR of OAEs in different frequencies in the right and left ears based on the exposure to different levels of sound pressure at different times. In this study, the model was highly in agreement with the actual values. One of the limitations of this study was the small number of DPOAE devices, which were prepared with much effort by the researchers.

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Nil.

Conflicts of interest

There are no conflicts of interest.

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